

DISCOVERY OF A DEEPLY EMBEDDED COMPANION TO LkH α 234

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ABSTRACT

We report the discovery of a deeply embedded young stellar object (YSO) 3" northwest of the Herbig Ae/Be star LkH α 234. This source (PS 1) is not seen in optical or near-infrared images. However, its existence is revealed by our 2 μ m polarization map which demonstrates that PS 1 partially illuminates a reflection nebula at the core of NGC 7129. PS 1 most likely is much less evolved than LkH α 234. PS 1 is very similar to a second deeply embedded object discovered recently in L1287 with the technique of infrared polarimetric imaging. These two YSOs may be representative of others that ultimately will be found hidden by dust near more evolved pre-main-sequence stars. Photometric observations centered on these pre-main-sequence stars have been presumed to represent flux from single stars surrounded by disks or other circumstellar structures. Models based on photometry, especially at mid-infrared wavelengths with large beams, therefore may have led to incorrect interpretations. Also, in many of these cases, an optically visible source is assumed to be the exciting star of a known molecular outflow. Our new result suggests instead that such energetic phenomena may be generated by heretofore undetected, less evolved sources.

Subject headings: circumstellar matter — infrared: stars — ISM: individual (NGC 7129) — polarization — stars: individual (LkH α 234) — stars: pre-main-sequence

1. INTRODUCTION

In some interpretations, the onset of a high-velocity molecular outflow signals the end of the protostar (Class I) stage of protostellar evolution and marks a transitional epoch (Class IID) after which a pre-main-sequence (Class II) star remains (Lada 1987). Since 143 of the 163 mapped molecular outflow sources are associated with deeply embedded YSOs (Fukui et al. 1993), this interpretation appears reasonable. The 20 optically visible pre-main-sequence stars that apparently drive outflows are exceptions. LkH α 234 (Edwards & Snell 1983) is among the most prominent of those exceptions.

LkH α 234 is an intermediate mass, pre-main-sequence Herbig Ae/Be star (8.4 M_{\odot} ; 1700 L_{\odot} ; Hillenbrand et al. 1992) associated with the optical reflection nebula NGC 7129. The distance to NGC 7129 has recently been estimated at 1.25 kpc (Schevchenko & Yakubov 1989). According to the analysis of Strom, Vrba, & Strom (1976), star formation may have begun in this cloud only a few times 10^5 yr ago. Two water masers, separated by 3", are located within 2" of LkH α 234. One is located $2'' \pm 1''$ to the northwest and the other $1'' \pm 1''$ to the southeast (Rodriguez et al. 1987). No optical or infrared sources are known within 4' of the star (Strom et al. 1976; Hartigan & Lada 1985).

Flux measurements of LkH α 234 using large beams yield $\alpha = +0.8$ (Mahesh 1993) for the slope of its spectral energy distribution (SED). Smaller beams, which isolate the star and eliminate reprocessed emission from extended structures or emission from companions, yield a much lower value, $\alpha = -0.2$. This latter value of α is more often associated with optically visible YSOs rather than embedded sources that

drive outflows. The latter value of α suggests that LkH α 234 may not be driving the molecular outflow observed in the region. Thus, if the outflow is active, the possibility exists that a heretofore undetected source, a less evolved and more deeply embedded protostar, is the exciting source for the outflow.

As demonstrated by our discovery of a deeply embedded YSO that apparently powers the molecular outflow in the dark cloud L1287 (Weintraub & Kastner 1993), infrared polarimetric imaging is a powerful tool for locating previously undetected sources such as might exist in NGC 7129. In this *Letter*, we report the results of our infrared polarimetric imaging study of the nebula surrounding LkH α 234. Our 2 μ m polarization map reveals the presence of a YSO located $\sim 3''$ northwest of LkH α 234. We also have found four additional near-infrared sources within $\sim 10''$ of LkH α 234, some of all of which may be part of a small star-forming cluster.

2. OBSERVATIONS

The data presented were obtained with an infrared camera (IRIM) through broad-band H and K filters on 1992 June 15 UT with the National Optical Astronomy Observatory 2.1 m telescope at Kitt Peak, near Tucson, Arizona.⁵ At the time of these observations, IRIM consisted of reimaging optics and a bandpass filter assembly placed in front of a 58×62 InSb detector array. A polarizing filter assembly (SLOPOL) consisting of a rotating half-wave plate and a polarizing analyzer was placed behind the warm focal plane. SLOPOL and our observing technique are described in detail in Weintraub et al. (1992). We obtained absolute photometric calibration at H and K with observations of the reference star σ Bootis and calibrated the absolute polarization position angle through K band observations of the polarized nebula CRL 2688 (Kastner 1990; Kastner & Weintraub 1993).

We collected two suites of polarized images through each filter. Each suite consists of four images, taken at 22.5 intervals

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of the half-wave plate polarizer. The integration times for each image in each suite were 60 s at H (co-adds of three 20 s exposures) and 50 s at K (co-adds of 10 5 s exposures). Shortly after beginning the H band observations, and before we obtained a complete polarimetric suite at this waveband, sky conditions changed and worsened; hence, we were unable to retrieve polarization information from the H images. Individual images were reduced by subtracting the bias and the dark current, dividing by a flat-field frame and subtracting the thermal background flux. As we have found that off-axis contamination was not significant in previous H and K band imaging programs using IRM (e.g., Weintraub et al. 1992; Weintraub & Kastner 1993; Kastner & Weintraub 1993), we used median filtered images of the sky to construct flat-field images. In addition, the high quality polarization maps of CRL 2688 obtained with these flats indicate that, for this telescope and imaging system and on this night, little if any off-axis thermal sources contaminate our images. The telluric background flux levels were determined from portions of each source image that were unambiguously off source. Unpolarized images with effective exposure times of 480 s (H) and 400 s (K) were obtained by co-adding the individual polarimetric images. In the unpolarized K image (Fig. 1), we detected four intensity peaks. The H image (not shown) reveals very little nebulosity; however, it reveals a fifth source not seen at K .

Positions, H and K band photometry, extinction-corrected $[H-K]$ colors for the objects detected in the vicinity of LkH α 234, and limiting magnitudes for the nebulosity are presented in Table 1. The larger errors in the H band photometry reflect the poorer observing conditions during which we collected these data. IRS 3 is clearly very red and LkH α 234 (IRS 1) is moderately red. If IRS 2 and IRS 4 suffer any local extinction in addition to the foreground extinction we have corrected for, they would be bluer than the moderately red colors indicated in the Table. Other than LkH α 234, none of the sources listed in Table 1 have been observed in previous studies of NGC 7129 (Strom et al. 1976; Hartigan & Lada 1985; Ray et al. 1990; Harvey, Wilking, & Joy 1984).

3. POLARIMETRIC EVIDENCE OF A DEEPLY EMBEDDED YSO

The polarization map obtained from the K band images is presented in Figure 2. Overall, the vector map reveals a circu-

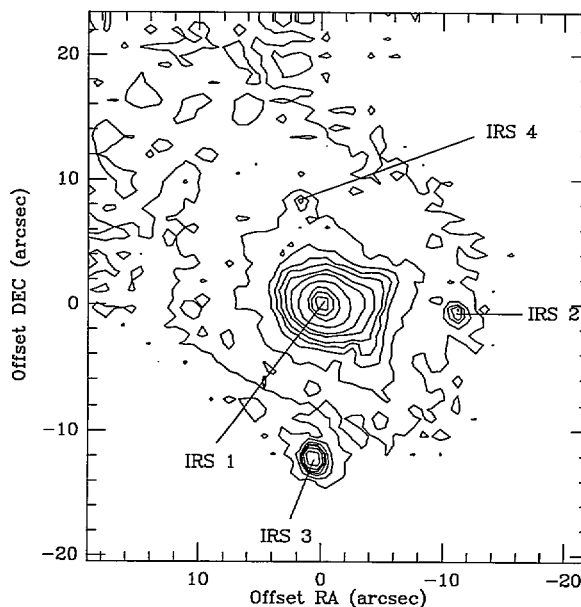


FIG. 1.— K band image of nebulosity surrounding LkH α 234 (IRS 1). Contour levels are 7.18, 7.86, 8.69, 10.12, 10.87, 11.26, 11.63, 11.87, 12.11, 12.62, and 13.76 magnitudes per square arcsec. Note that the nebulosity is extended to the northeast, the same direction as the CO outflow that is seen in this region. IRS 2–4 are identified. Two additional sources listed in Table 1 do not appear in this image; IRS 5 is seen only at H , and PS 1 is revealed only in the signature of the polarization map.

lar, nearly centrosymmetric pattern. On closer inspection, however, the centrosymmetry breaks up into two different patterns centered at different positions. The first pattern, to the northeast of LkH α 234, appears to be centered on the Ae/Be star. The second pattern, which dominates portions of the map west of the RA of LkH α 234, is centered about 3" west-northwest of the Ae/Be star. The central portion of the second pattern is elliptical, with major axis at position angle $\sim 31^\circ$. This elliptical pattern expands into a more circular pattern to the southwest out to a distance of at least 10" from the center. No point source appears at the center of the polarization ellipse in either the H or K images. As in the cases of certain star-formation regions (e.g., L1287, Weintraub & Kastner

TABLE 1
PHOTOMETRY AND POSITIONS OF SOURCES NEAR LkH α 234

Object	Offset Distance ^a	Offset PA ^a	[H] (mag) ^b	[K] (mag) ^c	[$H-K$] (mag) ^d	Aperture
IRS 1 ^e	0"	0°	8.75	7.72	0.72	5"6 × 5"6
IRS 2	7.5	270	14.08	12.86	0.92	2.1 × 2.1
IRS 3	10	175	>14.36	11.58	>2.48	2.8 × 2.8
IRS 4	6	15	14.10	12.90	0.90	2.1 × 2.1
IRS 5	2.5	330	14.36	>12.90	<1.16	2.1 × 2.1
PS 1 ^f	3	290–340	>14.36	>12.90	...	2.8 × 2.8
nebula	10.40 ^g	8.17 ^h	...	see notes

^a Offsets and position angles with respect to LkH α 234.

^b Estimated errors of ± 0.23 mag in absolute calibration.

^c Estimated errors of ± 0.15 mag in absolute calibration.

^d Color-corrected, assuming $A_H = 0.19A_K$ and $A_K = 0.10A_V$ (Becklin et al. 1978) and $A_V = 3.4$ (Hillenbrand et al. 1992) for all sources.

^e LkH α 234.

^f This source is identified only in the polarization map.

^g To a limiting magnitude of [H] = 14.52 per square arcsec; nebulosity covers a $\sim 9'' \times 9''$ region.

^h To a limiting magnitude of [K] = 15.48 per square arcsec; nebulosity covers a $\sim 32'' \times 32''$ region.

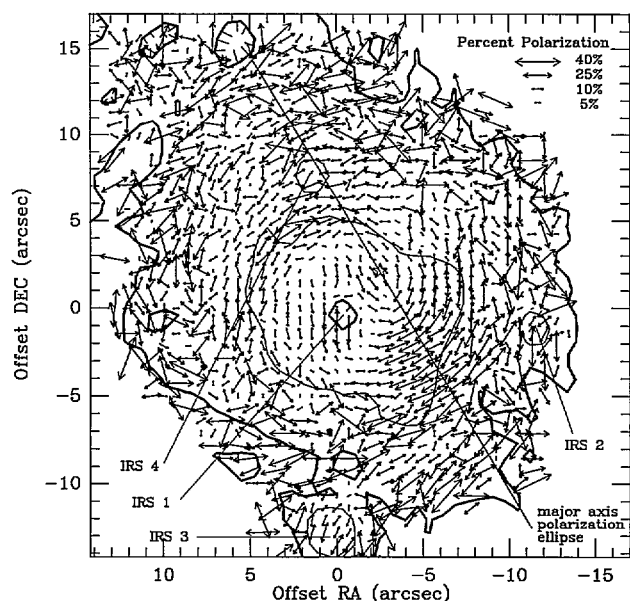


FIG. 2.—Polarization vector map of the central $30'' \times 30''$ portion of the $2.2 \mu\text{m}$ nebula around LkH α 234. A solid line at position angle 31° is drawn to mark the major axis of the polarization ellipse, which appears centered on the deeply embedded star PS 1 (marked by the star symbol). PS 1 is not detected directly in the K band image. Contours (heavy lines at 7.62 and 13.76 magnitudes per square arcsec; light line at 12.38 magnitudes per square arcsec) have been drawn from a smoothed (2×2 pixel) version of the image used in Fig. 1. The centrosymmetric pattern can be discerned out to the regions of limiting flux in the map. The low signal-to-noise levels in the outer regions of the map, however, cause the polarization pattern to become less organized.

1993; L810, Scarrott, Rolph, & Tadhunter 1991) and evolved bipolar nebulae (e.g., IRAS 093716+1212 and AFGL 2688; Kastner & Weintraub 1993), however, the latter polarization pattern very likely pinpoints the location of an embedded source (PS 1).

The centrosymmetric, nearly circular polarization pattern to the northeast of LkH α 234 apparently shows scattering by dust illuminated by LkH α 234. The pattern of polarization in the western region indicates that the embedded source PS 1 lies $3''$ from and at position angle $\sim 325^\circ$ with respect to LkH α 234. The separation and alignment of the two known water masers are nearly identical to those of PS 1 and LkH α 234. This suggests a possible one-to-one association between the masers and the two pre-main-sequence objects.⁶

4. ARE OUTFLOWS ALWAYS DRIVEN BY INVISIBLE SOURCES?

We have established (§ 1) that LkH α 234 is almost certainly more evolved than the typical driving source of a bipolar molecular outflow. The hidden protostar revealed by the polarization map is almost certainly a less evolved source, having no near-infrared counterpart. LkH α 234 may be sufficiently evolved such that an outflow once actively driven by this Ae/Be star turned off at the source relatively recently. If this is true, then the molecular material receding from the vicinity of LkH α 234 could be part of a fossil outflow from the Ae/Be star. It is also possible that the driving force once pro-

vided by LkH α 234 now has been supplemented by a more powerful force from the younger YSO. The polarization pattern we have measured does not appear consistent with such an explanation, however. Models of scattering (cf. Whitney & Hartmann 1993) predict that the major axis of a polarization ellipse surrounding a YSO should lie parallel to the line formed by the intersection of its circumstellar disk with the plane of the sky (i.e., perpendicular to its presumably coincident polar and outflow axes). Yet it appears that the projected axis of the disk of PS 1 is nearly parallel to the projected axis of the molecular outflow in this region (position angle $\sim 45^\circ$). Therefore, it is unlikely that PS 1 powers the large scale molecular outflow in the region unless the distribution and illumination of material in the vicinity of PS 1 is unusual, such that the major axis of its polarization ellipse marks its outflow axis. However, further modeling is required to determine whether a plausible distribution of dust grains and incident photons can produce a "polarization disk" whose major axis lies parallel to the YSO outflow axis.

This discovery of PS 1 is similar to our identification of a previously unknown source (possibly IRAS 00338+6312) in L1287 (Weintraub & Kastner 1993) and to the recent discovery of a deeply embedded companion to LkH α 198 in the L1265 cloud (Lagage et al. 1993). In all three cases, outflows were previously ascribed to visible pre-main-sequence stars. Similarly, from optical polarimetric imaging, Scarrott et al. (1991) predicted the position of L810 IRS, the near-infrared illuminator of a Bok globule in L810. This prediction was confirmed in the deep near-infrared images of Yun et al. (1993). These findings demonstrate the utility of optical and near-infrared polarimetric imaging as well as mid-infrared imaging as tools for revealing the presence of sources that may not be detectable directly at these wavelengths.

The presence of heretofore unknown mid- or far-infrared sources in L1287, NGC 7129, and L1265 suggests that several aspects of pre-main-sequence astronomy should be reexamined:

Many—perhaps all—optically visible (Class II) pre-main-sequence stars that appear to drive active outflows may be associated with less evolved (Class I) companions. Twenty optically visible sources, most of which are Class II, have been associated with outflows (e.g., T Tauri). Such associations are not in keeping with the evolutionary distinction between Class I and Class II sources, unless these are transition objects. The results presented in this Letter demonstrate that upon closer inspection, less evolved sources may be found proximate to well-known, optically visible sources. In fact in the T Tauri system, as in L1287, L1265, and perhaps NGC 7129, the outflows might be driven by infrared companions rather than by the optically visible stars.

Optically identified pre-main-sequence stars that are classified as Class I may be multiple systems with Class I and II components and are generally found in or near cold clouds. A great deal of care must be exercised in fitting models to the SED curves of these systems. Some optically visible, Class I sources are associated with outflows and nebulosity. LkH α 234 is a good example. Because such sources are optically visible, they clearly suffer much less extinction than many YSOs. Thus, these pre-main-sequence stars may be Class II sources, misidentified as Class I. They may be misclassified because the classifications have been made with flux densities measured in apertures of very different sizes. The photometric data points included in the SEDs of these pre-main-sequence stars may

⁶ Cabrit & Lagage (1993) report the discovery of a $10 \mu\text{m}$ source located northwest of LkH α 234, at the approximate position predicted by our polarimetric map.

combine the fluxes from two or more sources or from a source and a large surrounding cloud. If such sources are reclassified using flux densities from observations with better matched apertures, many or all of them may be found to be Class II objects. The more evolved classification would make more sense given the small visual extinction associated with bright sources. It would also make the associations of these stars with outflows either less likely or more anomalous.

Additional near-infrared polarization imaging of bright optical or near-infrared stars associated with molecular outflows may reveal that many more members of this unusual group of prestellar objects have much less evolved, deeply

embedded companions. If so, we may find that the bright stars have been misclassified and in some cases the less evolved sources drive the outflows. High-resolution mid-infrared and mm-wavelength imaging also hold promise for revealing additional sources not directly detectable in the optical or near-infrared. By revealing the existence or demonstrating the absence of additional sources in these regions, such studies will significantly advance our understanding of role of the outflow process in protostellar evolution.

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